# Tensor Fluxgate Gradiometer Development

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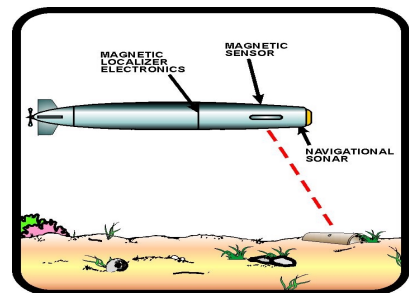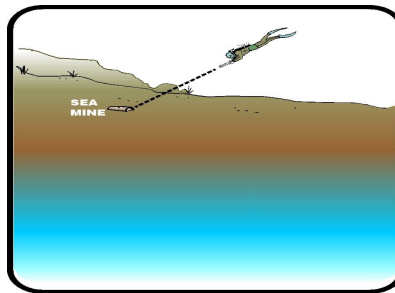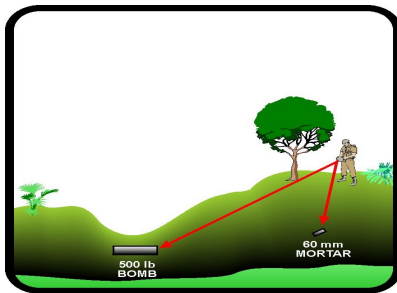phone: (850) 234-4682  fax: (850) 235-5462  email: wynnWM@ncsc.navy.mil

## LONG TERM GOAL

Our long-term goal is to provide a robust suite of algorithms capable of performing real-time localization of both isolated and grouped ferromagnetic targets.  It is intended that these algorithms be applicable to any tensor magnetic gradiometer system used for surface or subsurface platforms.  These algorithms will be most robust when used in conjunction with conventional navigational systems, but will also be provided with a self-navigating capability that exploits the magnetic fields and gradients of the sources being localized.

## OBJECTIVES

The objectives of this task are (1.) use the prototype tensor fluxgate gradiometer developed by Quantum Magnetics as a phase I SBIR product, to collect an extensive data base using a wide variety of ordnance and standard magnetic sources under several conditions,  (2.)  Refine, extend, and create algorithms for both point-by-point homing and precision mapping of magnetic sources, (3.) to evaluate and fine tune the algorithms using the established data set, and (4.)  Produce a self contained user friendly computer code for application with the planned Quantum Magnetics SBIR phase II product as well as  superconducting gradiometers developed at the Coastal Systems Station.



*1.  Potential Applications*

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## APPROACH

The approach is to take the several algorithms developed over a period of several years under a low-level, independent research effort and adapt them to into user-friendly code capable of performing under a wide range of platforms and conditions. These algorithms, some of which have already been patented and others are or in the process of being patented, are capable of converting magnetic gradient data into information about the magnetic moment vector, position vector, and relative motion of sensor and source.  When precise navigational information is available, these algorithms are expected to be relatively easy to implement.  To investigate this mode of operation, we have incorporated a differential GPS sensor mounted on a cart along with the tensor gradiometer, Figure 2.  Without a navigational capability, Figure 3, the localization process is much more difficult.  It would be highly desirable if magnetic sources could be precisely located relative to the operator using only magnetic information generated by the source.  Considerable progress has been made in connection with this latter problem, but much work still remains to be done.  One of the most critical issues has been and remains the determination of the absolute orientation of the magnetic sensor platform in space.  This knowledge is essential both to the removal of the effects of natural background magnetic gradients, and to the correction of the magnetic gradients of a target source during final localization.
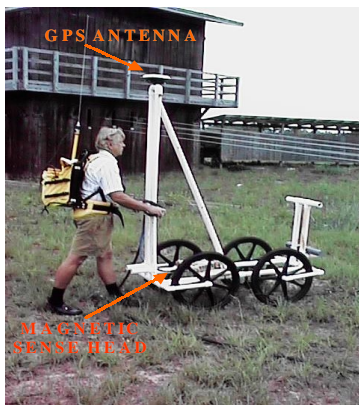


*2.  Cart mounted sensor with GPS*



*3. Hand carried sensor w/no nav aids*

To date, our efforts have focused on the use of accelerometers to augment the measurement of the earth's magnetic field vector and provide absolute orientation.  This effort has had limited success, as reported in the FY 1998 annual report.  In FY99 we investigated the use of rate gyros to establish the platform orientation by integrating the platform angular velocity vector, at least for limited time periods.  We are transitioning our balancing and localization algorithms to a fully interactive user-friendly software environment based on Hewlett-Packard's VEE programming language and are establishing an extensive database with the RTG in several configurations.  Also, we are investigating serious noise problems with the RTG when used in a hand-carried mode.

## WORK COMPLETED

**Experimental**:  We purchased a 3-axis rate gyro from Systron-Donner and mounted it on a separate platform that can be attached directly to the RTG sensor, Figure 4.  This sensor produces voltages proportional to the angular velocity vector components along the three axes of the sensor.  We have performed measurements of the influence of the rate sensor on the RTG, both due to the applied power

to the rate sensor, and due to the presence of the magnetic material of the rate sensor adjacent to the RTG when it is in motion. We have conducted the motion experiments both on the CSS shake table and on a shoulder-mounted board transported by a person walking. In the process of taking these measurements we have collected an extensive rate-gyro database of target signatures and RTG motion noise under a variety of motion conditions. We also have taken target data with the GPS sensor directly mounted to the RTG, both hand carried and cart-mounted.
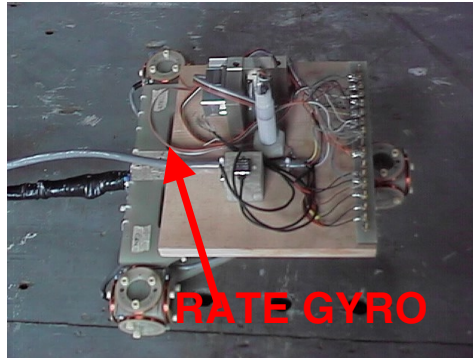


*4.  Rate gyro attached to RTG sensor*

**Theoretical:** We have developed the basic equations for using the angular velocity vector measured by the rate sensor to compute the rotational contribution to the time variation of the magnetic gradient tensor.

**Software:**  We have written and demonstrated a Hewlett-Packard VEE program that performs fixed parameter motion compensation of the Gradiometer data coming directly from the VXI bus, computes estimates of the gradient rate tensor, performs instantaneous homing to a target via an imbedded Dynamic Link Library (DLL) program, and displays the bearing vector to the target and the direction of motion of the sensor relative to the target without using an external navigational reference.

**General:**  In addition to ancillary sensor selection and algorithm development considerable effort has been spent in a quest for a transition path. As evidenced by entries in the publication section, considerable effort was spent in marketing to the Autonomous Underwater Vehicle (AUV) community.

**RESULTS**

**Experimental:**  We have found that the power currents associated with the rate sensor create significant magnetic signals at the RTG sensors. The effect is as large as 10 nanotesla per foot equivalent gradient. It is apparent from this data that the stability of the currents supplying the rate sensor must be one percent or better to keep this noise source from degrading the RTG performance.

To investigate the influence of the rate gyro on RTG motion noise, we placed the RTG on the CSS shake table and performed a fixed parameter balance run without the rate sensor attached and then with the rate sensor attached. There is a slight increase in some of the gradient channels, but not enough to matter, at least with the gentle, low-frequency motions of the shake table. We continued the investigation with the RTG and rate gyro combination in man-portable mode. The assembly was rotated by hand, followed by walking with the sensor and using the fixed parameter balances found from the standing rotation. We found a significant increase in the motion noise during walking. The

implication of this data is that fixed parameter balancing is inadequate when there is higher frequency motion. Under the ONR funded High Critical Temperature (HTC) superconducting gradiometer development program, parallel analysis was also done in FY 1999, with good results, addressing a full frequency-domain treatment of motion noise compensation. In this approach, the connection between the gradiometer motion noise and the earth's field reference channels is treated as a multi-channel linear system problem. We have taken data with the RTG without the rate sensor attached, while the sensor was carried at a brisk walk. We then compared the stationary noise, the residual noise after fixed-parameter balancing, and the residual noise after frequency-domain compensation. The results are shown in Figure 5. It is clear from these results that a full frequency-domain multi-channel transfer function treatment is required in order for the RTG to achieve the design noise specification while in motion. This capability has not been incorporated into the real-time software in FY 1999.

**Theoretical:** In the interactive localization algorithm that was refined under the FY 1999 effort, it is assumed that the time rate of change of the measured gradients is generated strictly by the translational motion of the RTG past the stationary magnetic source. In fact, the sensor will rotate in the presence of the target, and part of the time rate of change in the gradients is due to this rotation, and causes a departure from the assumptions of the localization model. This rotation in the gradient and its characterization was the principal reason for adopting rate gyros as part of the sensor package. Then

**RESIDUAL PSDS STATIONARY AND BRISK WALK**
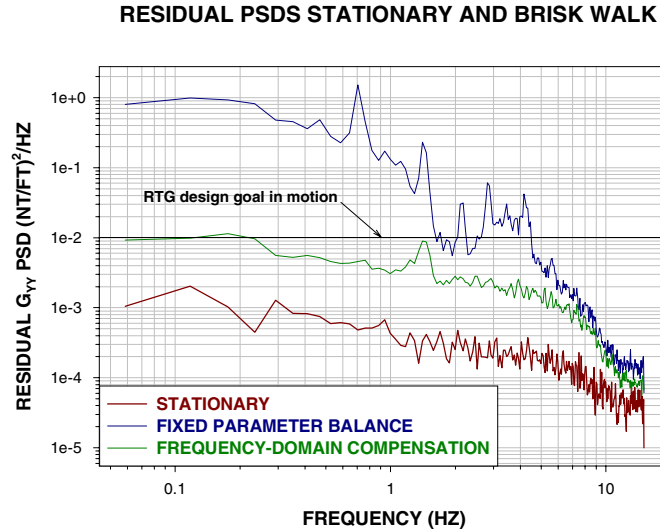


*5. Residual PSDs for stationary and brisk walk*

the issue is how to use is the angular rate information to separate the two contributions to the time rate of change of the gradients. We address the theoretical basis for this here. The fundamental equation is

$$\frac{d\mathbf{G}}{dt} = \frac{\partial \mathbf{G}}{\partial t} + \frac{d\mathbf{R}}{dt} \times \mathbf{G} - \mathbf{G} \times \frac{d\mathbf{R}}{dt}$$

where $\mathbf{G}$ is the 3x3 matrix of gradient tensor components, $\mathbf{R}$ is the 3x3 instantaneous rotation matrix, and the first term on the right is the translational rate of change of the gradient tensor---the one needed in the localization algorithm. This is the system of equations that must be solved to isolate the translational time rate of change of the gradient tensor. It currently has not been incorporated into the real-time localization software.

**Software:** We have chosen to use the Hewlett-Packard VEE software environment to develop real time operating software. The latest program inputs 12 channels of raw data from the RTG, motion compensates and forms the gradients, computes the time rate of change of the gradient tensor, calls the localization Dynamic Link Library, and provides a display (Figure 5) which plots the horizontal projection of the bearing vector to the target in the upper right panel, and the horizontal projection of the unit velocity of the sensor relative to the target in the lower right panel. Also shown are the individual gradient channels, the magnitude of the gradient tensor, the individual gradient rate channels, and the magnitude of the gradient rate tensor. The data illustrated in Figure 6 is from a hand-held pass by a 1000 lb bomb-sized target at a lateral distance of 10 feet.
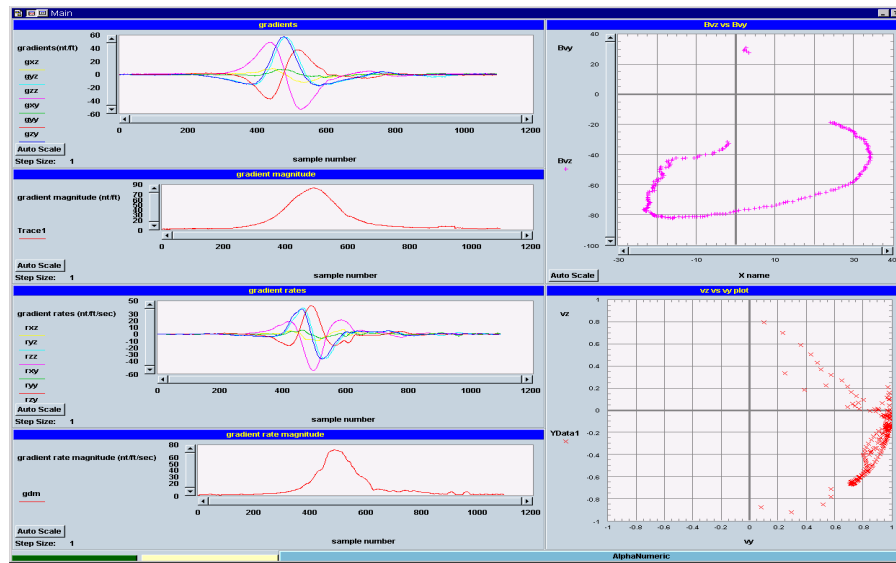


*6. Panel view of Hewlett Packard VEE program output.*

## IMPACT/APPLICATION

This demonstration of localization using magnetic signature information allows instant standoff mapping without the need for elaborate grid searches. It will allow the safe avoidance of potentially dangerous targets while providing accurate mapping in a real time scenario.

## TRANSITIONS

The funded effort is currently scheduled for completion at the end of FY 1999. Our goal was to provide a complete set of localization/tracking algorithms compatible with a variety of magnetic gradiometers. Because of unexpected motion noise issues, we have not met this goal and will request some additional funding. Originally, the planned transition using the RTG sense package was to have been to the Diver Portable Buried Mine Hunter Task under the Mission Support Project CSS#20114. However, in FY98 that effort was refocused to develop only sonar technology. Because of the generic nature of magnetic tracking/localization, several additional areas and applications are considered potential transition paths. Two broad areas of consideration are; UneXploded Ordnance (UXO) localization and Autonomous Underwater Vehicle (AUV) applications. While the delivered algorithms will be specifically tailored to the RTG sensor in terms of gradient requirements and sensor sensitivities, they are easily adjusted to a wide range of sensors that provide magnetic gradient data. The completed software package developed under this task combined with the SBIR Phase II man-portable sensor from Quantum Magnetics delivered late in 1999 will provide an unexcelled standoff

detection/localization system for the localization and mapping of UXO and other land based targets. Underwater applications will require limited modifications to replace the GPS data with suitable underwater navigational information as well as other changes to accommodate the required platform.

## RELATED PROJECTS

The CSS Magnetic Sensors project #21325 is developing a liquid nitrogen based, superconducting gradiometer system capable of detecting ferromagnetic underwater objects from a moving platform. It has greater projected sensitivity but is not man portable and will require cryogenic fluid. Much of the localization code being developed in this task will be applicable to that activity with little modification.

## REFERENCES

None

## PUBLICATIONS

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2. W. M. Wynn, *Magnetic Dipole Localization with a Tensor Gradiometer: a Rigorous Analysis Including Relative Motion,* in <u>Proceedings of the 2<sup>nd</sup> International Conference on Marine Electromagnetics</u> , pp. 295-304, ENSIETA, Brest, France, June 5-7, 1999

3. G. Allen, *Operating a Sophisticated Magnetic Sensor Aboard a Standard AUV*, <u>Eleventh International Symposium on Unmanned Untethered Submersible Technology (UUST99),</u> Autonomous Undersea Systems Institute (AUSI), August 1999, pp 238-247.

## PATENTS

PATENT SUBMISSION: *Method of Determining Magnetic Source Bearing and Sensor Direction of Motion using Gradient Tensor Components and Rate Tensor Components without External Navigational Reference*, by W. M. Wynn.